International Journal of Engineering Research
Volume No.5, Issue No.8, pp : 717-720

ISSN:2319-6890)(online),2347-5013(print)
1 August 2016

# 2.1 MW Wind Turbine Performance and Dynamic Analysis using Power Curve

**Vasishta bhargava[1], Balaji Krushna.P[2] , KVRS Sairam[3]**
GITAM University, Hyderabad, Telangana
vasishtab@gitam.in[1] , balajikrushna@gitam.in[2], sidkvr@gitam.in[3]

***Abstract: Power curve analysis of wind turbine is done using measured data available for a specific wind turbine which has rated power of ~ 2.1 MW with a rotor diameter of 95m and with hub height of ~ 90m. Performance of a wind turbine is dependent upon the parameters namely power coefficient, Cp, Torque coefficient, Ct and Thrust coefficient, CT. The operating state of a turbine is estimated using blade pitch angle position, rotor rotational speed, between, cut-in, rated and cut-out wind speeds. They are specific to a given turbine configuration, as well as the characteristic of turbine technology used. Data analysis shows values of 0.41 & 0.43 for Cp, a maximum value of 0.95 for CT and ~0.08 for Ct. Analysis of turbine design includes blade rotational speeds and pitch angles, design tip speed ratio. Time series analysis of data set establishes the dynamic turbine behaviour for electric power, main shaft torque.***

**Keywords: Wind turbine, blade, power coefficient, thrust co-efficient, tip speed ratio, Power curve.**

**Nomenclature**

R =Blade length, (radius) m; V= wind speed, m/s, A = Swept area, $m^2$, $\rho$ = Air density,

$$C_t = \text{Torque coefficient} = \frac{T}{0.5\rho\pi R^3 V^2};$$

$$TI = \frac{\text{Standard deviation of wind speed}}{\text{Mean wind speed}} = \frac{\sigma}{\overline{V}}$$

$$C_p = \text{Power coefficient} = \frac{P_e}{0.5\rho\pi R^2 V^3};$$

$$C_T = \text{Thrust coefficient} = \frac{F}{0.5\rho\pi R^2 V^2}$$

DFIG = Doubly Fed Induction Generator, BEM = Blade Element Momentum,
IA – Type class: TI – A (0.16); I-10m/s, IIB -Type class: TI - B (0.14); II - 8.5 m/s,
IIIC –Type class: TI – C (0.12), III-7.5m/s,
TI = Turbulence intensity, TSR = Tip Speed Ratio.

## 1. Introduction

Wind turbine extract power from wind utilizing the amount of wind available in a site. Modern wind power technology utilizes three blades and horizontal axis orientation at a specific hub height. The power production from turbine is controlled using blade pitch angle and rotor speed. The performance characteristic of typical wind turbine is carried out using its power curve with following configuration.

**Table 1.Key turbine parameters**

| | |
|---|---|
| Turbine type class | IIA / IIIB |
| Hub height, m | ~ 90m |
| Rated power,kW | 2100 |
| Rotor diameter, m | 95 |
| No of blades | 3 |

## 2. Power curve and Performance characteristics

At a given site location, the wind turbine produces power within a range of wind speed values. Therefore, power curve considers bounded regions commonly referred to

- Cut-in wind speed - Start of active power production between 2.5 to 5m/s
- Rated wind speed - Produces the rated capacity of generator power.
- Cut-out wind speed – Disconnects the machine from the grid.

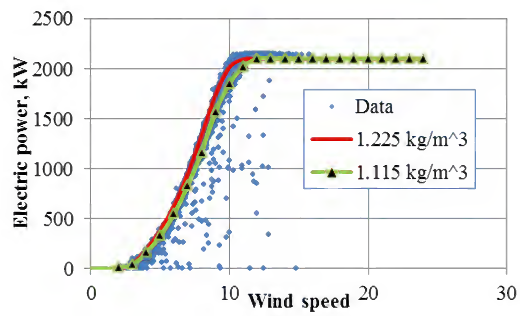


**Fig 1. Power curves of manufacturer & measured data, 1 month data**

The data available for a specific site location, for the machine is approximately, 742 hours (~ 30-31 days or 4410 10 min data points). This data is often measured as 10 minute averaged values and according to the IEC 61400-12 regulations for power curve performance. Important data pertaining to the power curve has following parameters

- Wind speed, m/s,
- Electrical power, kW, DFIG Active power
- Wind direction, degrees

Turbulence intensity is evaluated using the standard deviation of wind speed for a site. For one month data, the TI values and the wind speed frequency is shown in table. Using the available data the turbulence intensity of site class cannot be known accurately however, the table indicates the TI values decay at higher wind speeds while the standard deviation of wind speed remained steady indicating a low to medium turbulence site. The

ISSN:2319-6890)(online),2347-5013(print)
1 August 2016

difference in the values for measured and manufacturer can be attributed to site air density for the data considered in the analysis.

| | Electric power, kW | | Power coefficient [-] | |
|---|---|---|---|---|
| WS, m/s | Standard | Measured | Standard | Measured |
| 1 | 0 | -1.2 | 0.000 | -0.298 |
| 2 | 0 | -0.6 | 0.000 | -0.019 |
| 3 | 0 | 10.5 | 0.000 | 0.099 |
| 4 | 48.3 | 41.5 | 0.174 | 0.164 |
| 5 | 190.7 | 164.0 | 0.351 | 0.332 |
| 6 | 383.5 | 329.8 | 0.409 | 0.386 |
| 7 | 631.4 | 549.3 | 0.424 | 0.405 |
| 8 | 955.2 | 831.0 | 0.430 | 0.411 |
| 9 | 1338.4 | 1164.4 | 0.423 | 0.404 |
| 10 | 1744.8 | 1535.4 | 0.402 | 0.389 |
| 11 | 2016.3 | 1855.0 | 0.361 | 0.353 |
| 12 | 2096.4 | 2029.3 | 0.311 | 0.301 |
| 13 | 2100 | 2101.5 | 0.251 | 0.245 |
| 14 | 2100 | 2101.6 | 0.201 | 0.196 |
| 15 | 2100 | 2102 | 0.163 | 0.160 |
| 16 | 2100 | 2102 | 0.135 | 0.132 |

**Table 2.Comparison of electric power, & power coefficient values**

| Wind speed | | TI |
|---|---|---|
| Frequency | Stdev | % |
| 7 | 0.151 | 15.12 |
| 47 | 0.261 | 13.04 |
| 182 | 0.269 | 8.95 |
| 355 | 0.287 | 7.18 |
| 363 | 0.293 | 5.86 |
| 359 | 0.296 | 4.93 |
| 476 | 0.289 | 4.12 |
| 579 | 0.286 | 3.57 |
| 687 | 0.289 | 3.21 |
| 496 | 0.294 | 2.94 |
| 454 | 0.301 | 2.74 |
| 261 | 0.286 | 2.38 |
| 108 | 0.263 | 2.03 |
| 21 | 0.311 | 2.22 |
| 10 | 0.300 | 2.00 |
| 3 | 0.321 | 2.01 |

**Table 3 Wind speed frequency distribution and Turbulence intensity for data.**

From manufacturer power [i] curve, the cut-in wind speed is noted as 3.5 m/s, rated wind speed is 11 m/s and cut-out is 25 m/sand depend according to site and turbine operator requirement. The active energy and reactive energy for the measured data are 0.7691 GWh and 0.07 GWh while the net energy for one month data (~ 742 hours) is found to be 0.701 GWh. The wind speed frequency and energy distribution at a site location can be described in terms of Weibull distribution. It utilizes the shape and scale factors for the characterization of site location. The shape factor takes into account the roughness of site location, orography, while the scale factor considers the annual mean wind speed prevalent at site and evaluated using the formula [ii]

$$f(V) = k.\frac{V^{k-1}}{c^k}.e^{-\left(\frac{V}{c}\right)^k};$$

$$\bar{V} = \int_0^\infty Vf(V)dV;$$

$$c = \frac{\bar{V}}{\gamma(1+\frac{1}{k})}$$

Where k, represents shape parameter indicating the variation around mean wind speed in the site and c the scale parameter and V represents the wind velocity. f(V) is density function. The scale factor is derived from the gamma function in terms of shape factor for which the $\bar{V}$ is annual mean wind speed at site is known from wind zone [i] The probability density function for different values of shape factor at a given wind zone has been calculated and plotted in graph as

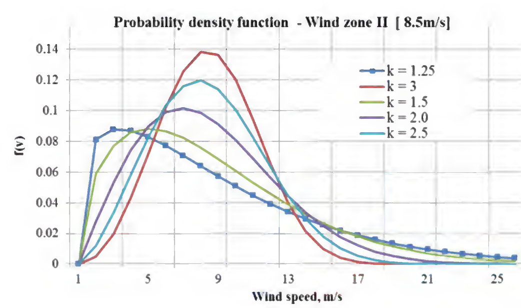


**Fig2.Weibull distribution at different shape factors**

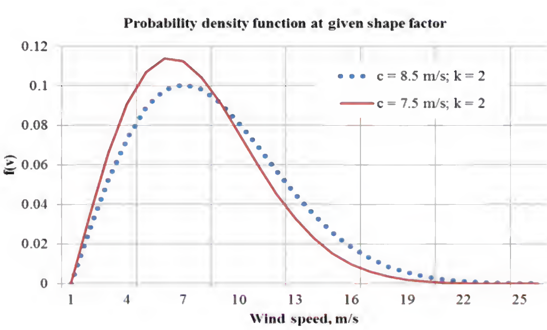


**Fig3. Weibull distribution at given shape factor for different wind zones**

It can be observed that as the annual average wind speed at a site is increasing, the maximum energy extracted from the turbine also increases. Further, the frequency distribution at higher wind speeds is also higher at higher wind zones i.e. II and III respectively. The weibull energy derived from power curves of 95m rotor is shown in table below

**Table 4.Weibull energy comparison using power curve, 2.1MW & 95m rotor**

ISSN:2319-6890)(online),2347-5013(print)
1 August 2016

| Wind Zone | PC Type | Weibull hours | Scale factor | Shape factor | Weibull Energy [GWh] |
|---|---|---|---|---|---|
| II | Measured | 712 | 9.5 | 2.1 | 0.662 |
| | Standard | 712 | 9.5 | 2.1 | 0.725 |
| | Measured | 641 | 9.2 | 1.3 | 0.474 |
| | Standard | 642 | 9.2 | 1.3 | 0.510 |
| III | Measured | 624 | 8.4 | 2.1 | 0.575 |
| | Standard | 624 | 8.4 | 2.1 | 0.634 |
| | Measured | 416 | 7.77 | 1.1 | 0.386 |
| | Standard | 416 | 7.77 | 1.1 | 0.416 |

The monthly energy, GWh, is obtained using the excel WEIBULL function and represents the theoretical maximum for the given type class. It assumes no downtime i.e. without considering the operation and maintenance and other factors. Weibull energy for two different wind zones, II & III have been calculated, using the power curves, measured at 1.225 & 1.115 $kg/m^3$ respectively. It can be observed that energy difference due to a change in the shape and scale factor is ~ 33 % i.e. k=2.1 to 1.3 and ~13 % difference due to change in wind zone, i.e. II to III, in which the turbine operates The swept area A, of the turbine is ~7085 $m^2$ for 95m rotor. It indicates the quantum of wind volume captured by the turbine rotor during power production. Also manufacturers consider factors such as hub height, blade technology i.e. aerofoil geometry profiles for power production improvements and thus considered beneficial.

## 3. Results and Discussion

The operating state of turbine can be described by four main conditions

- Idling i.e. no power generation, below cut-in and above cut-out wind speeds.
- Power production – active power production fed to the grid.
- Start-up of machine by the controller settings.
- Shut down of machine due to external conditions such as 50 year gust wind, grid loss events, low wind speed regime.

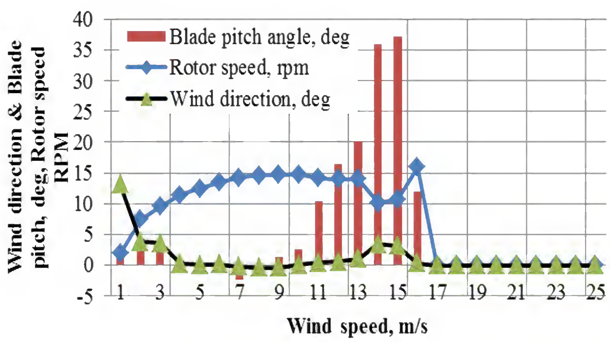


**Fig4. Blade pitch angle characteristics observed with rotor rpm & direction**

The turbine performance is determined using two parameters namely, power coefficient, Cp and thrust coefficient, CT and are calculated using the blade length of 47.5m. Below rated wind speeds, turbine controller tries to maximize rotor efficiency and maintain constant Cp. For a pitch controlled turbine the blade is gradually turned out of wind above rated wind speed during which the mechanical power extracted from the wind remains constant mainly to protect generator from excessive loads. This often results in the efficiency reduction. Using power curve methodology, statistical method is applied on bins for the 10 min averaged data set and it shows that maximum power value obtained is 2141 kW above rated wind speeds. The thrust force is used for calculating the CT[iii], while main shaft torque for calculating Ct respectively.

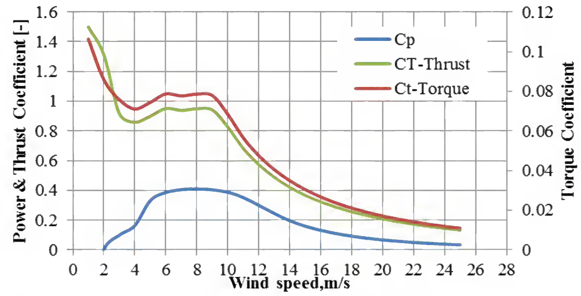


**Fig5. Thrust, Power & Torque coefficients, CT, Cp & Ct for 95m turbine rotor**

The average blade pitch angle positions range from -2 deg to 10deg during power production regime and the maximum blade angle in any bin is found to be 90 when the turbine blade is stopped. Below rated wind speed, the pitch angle is close to 0 deg. The rotational speed of rotor is 14-15.9 RPM range at which maximum blade tip speed is 79.08m/s. The "Tip speed ratio," is measure of rotor angular speed, blade radius and varies with apparent wind velocity. For a fixed speed turbine i.e. constant rotor speed, TSR reaches optimum value at only one wind speed, however for variable speed turbine; the TSR occurs at value that corresponds to maximum Cp by controlling rotor speed.

Normally measurements of wind speed and directions are done by the anemometer at hub height and wind vane sensors. The position of sensors is behind the rotor on the nacelle which results in inaccurate readings. The power produced is therefore controlled using the measured rotor speed and their actual characteristic is shown in Fig 4 below. It can be observed rated power is reached at a speed of ~1569 rpm at which generator slip is found to be -4.6%.

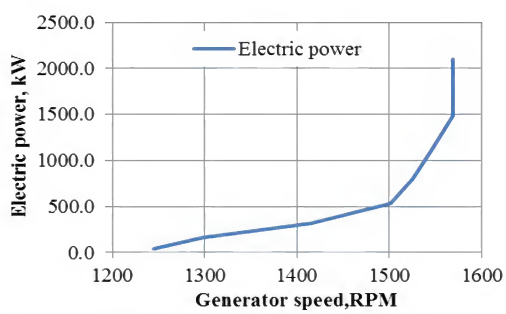


**Fig6. Generated power vs measured speed characteristic for the turbine**

Overall design tip speed ratio for a given machine can be obtained using the Fig 5 below. It can be seen from graph

ISSN:2319-6890)(online),2347-5013(print)
1 August 2016

that the tip speed ratio value is also 5.82, at 8 m/s using derived power curve. When the manufacturer power curve is used for the Cp calculation, at air density of 1.225 kg/m$^3$, a higher value of Cp, ~ 0.43, at 8m/s is obtained than that from the current data assessment due to site air density change. Since only month data is available the design tip speed ratio can be estimated to be 6.01 as $(1.225/1.115)^{1/3}$ x 5.82. The maximum thrust, torque coefficients occur near cut in wind speeds and found to be 0.95, 0.08, respectively while the Cp for measured data value of 0.41 is found near rated wind speed, 8 m/s.

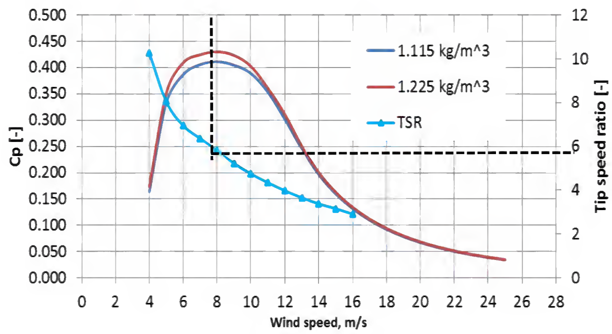


**Fig7 .Design tip speed ratio determination method**

The time series data analysed for various conditions depict the turbine operation for a period of 1.5 days. However, the electric power, main shaft torque reach lower values, near the 90-110 time stamp, due to the low wind speed regime occurrence. The data pattern shows fluctuations for main shaft torque and electric power due to the change in the wind speed regime in the site and as low as 160 kW and 124.3kN-m respectively but near cut in value, and rise to rated values, ~ 2100kW and ~1285 kN-m at the wind speeds 11-12m/s. With the data analysis the maximum rotor thrust of 324.8 kN, torque of 1285 kN-m and electric power of 2141.1kW are experienced by the turbine.

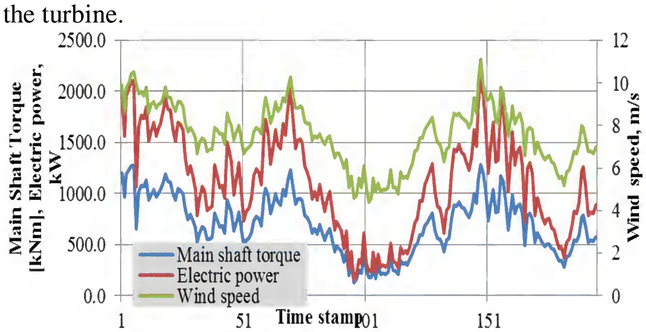


**Fig 8. Time series trend of main shaft torque, electric power, wind speed, m/s**

## 4. Conclusions

Site Characteristics: The shape and scale factors from weibull distribution enables to predict the wind speed frequency and energy available at a given site location. Using the given measurement data the net energy produced during any period is obtained by deducting the reactive energy from the active energy. From frequency distribution table it can be concluded that the turbine operates more time in the high or constant Cp region of the power curve below rated values than above rated values.

Performance coefficients Cp, CT, indicate the measure of efficiency, and depend upon factors namely, average site air density, the blade pitch angles, rotor speed states. The efficiency of the turbine also depends upon the blade length or the span. The torque, thrust and power coefficient values are ~0.08, 0.95 and 0.41 which is in accordance with the BEM theory. For manufacturer power curve data the maximum power coefficient is 0.43 for 95m rotor. Design parameters*:* The average blade pitch angle positions range between -2 to 10 deg where most of the power production occurs. Design tip speed ratio is found to be 6.01 for 95m rotor. From data analysis, the nominal slip of generator is -4.6 % and calculated using the synchronous speed of generator. The generator slip remains constant for near rated and above rated values.

## 5. Acknowledgements

The authors wish to thank Mytrah Energy India Limited, Hyderabad in providing the one month data used in the analysis.

## 6. References

*i.. Directory Indian Wind Power,2012, Consolidated Energy Consultants, Bhopal. India.*

*ii.. Tony Burton, David Sharpe, Nick Jenkins, et al. Wind Energy Handbook. John Wiley & Sons Ltd, 2005.*

*iii..Haibo Jiang, Zhongqing Cheng, Yungpen Zhao, "Torque limit of Horizontal Axis Wind turbine", Proceedings of International Conference Mechanical Engineering & Materials Sciences, MEMS 2012.*

*iv. S.N. Bhadra, D.Kastha, S. Banerjee. Wind Electrical systems. Oxford Higher Education. 2010.*